DEVELOPMENT OF A NEW RECTANGULAR BOX-SHAPED STANDARD AMMUNITION STORAGE MAGAZINE

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ABSTRACT

A new, earth-covered, standard magazine for the storage of ammunition and explosives is being developed by the U. S. Army Corps of Engineers. The new magazine is to be constructed using the Blast and Fragment Resistant (BFR) wall system, also known as the Agan Steel Panel (ASP) system. The magazine is a rectangular box structure with a flat roof. It is anticipated that this magazine will be approved as a standard magazine for storage of up to 500,000 pounds net explosive weight, in accordance with DOD 6055.9-STD. If approved, it will become the first standard magazine approved on the basis of design using the methods in the U. S. Army Technical Manual TM 5-1300. The magazine will permit storage of large quantities of explosives at standard intermagazine distances, and it will provide the advantages of a rectangular shape rather than a circular or oval arch.

This paper discusses the background behind the development of the new box-shaped magazine, the basis of design and blast loading assumptions used, the configuration and details of the new magazine, and advantages over the existing standard magazine designs.

INTRODUCTION

The Blast and Fragment Resistant (BFR) wall system was developed for use in structures subjected to the effects of conventional weapons. The BFR system is a composite structure of exterior steel face panels, tied together with internal, diagonal steel lacing panels, and filled with concrete. The system has been extensively tested for its resistance to explosions of in-

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Table 3. Predicted Peak External Pressures

Location		Peak Pressure (psi) for Test No,			
Azimuth (Degree)	Range (ft)	1	2 & 4	3 & 5	6
Front (0)	20	5.59	4.56	4.46	7.51
	30	3.38	2.67	2.60	4.39
	40	2.38	1.84	1.79	3.00
	55	1.60	1.21	1.17	1.97
	75	1.09	0.80	0.77	1.30
	100	0.77	0.55	0.53	0.88
	150	0.46	0.32	0.31	0.52
Diagonal (30)	40	2.03	1.48	1.43	2.41
	55	1.39	0.99	0.95	1.60
	75	0.96	0.66	0.63	1.06
	100	0.67	0.45	0.43	0.73
Side (90)	15	3.44	1.66	1.48	2.50
	20	2.68	1.39	1.26	2.13
	30	1.83	1.00	0.92	1.56
	50	1.09	0.61	0.56	0.93
	75	0.70	0.39	0.35	0.60
Back (180)	55	1.60	1.21	1.17	1.97
	100	0.77	0.55	0.53	0.88
	150	0.46	0.32	0.31	0.52

covered, concrete, oval-arch magazine found in U. S. Army Corps of Engineers Standard Drawings 33-15-74 [2].

The ultimate goal of this development effort is to obtain approval of the BFR magazine, by DDESB, for use as a standard magazine. However, it is our goal to develop a magazine that will be approved on the basis of design alone rather than testing. If approved, the BFR magazine will become the first standard magazine to be approved without actual explosive testing.

BFR WALL SYSTEM DEFINITION

The BFR wall system is a composite of steel and concrete. The exterior surfaces of a BFR wall consist of thin, lightly corrugated, steel face panels. These panels are usually manufactured in widths of 200, 250 and 300 mm (approximately 8, 10 and 12 inches) and lengths as required. Corresponding thicknesses of these panels are 0.8, 1.0 and 1.2 mm, respectively. The face panels interlock at ribs along their vertical edges to form a continuous exterior steel surface. The front and rear face panels are tied together using diagonal steel panels, referred to herein as lacing panels. The lacing panels are arranged between the face panels in a zig-zag pattern and are attached to the face panels with sheet-metal screws. The lacing panels vary in width to match the specific face panel dimensions and are generally 0.6 mm thick. This assembly of steel sheets is filled with a high-slump concrete mix. Holes are provided in the lacing panels to allow the flow of concrete between the panels. When assembled, the thickness of the wall is the same as the width of the individual face panels. Therefore, finished BFR walls are available in thicknesses of 200, 250 and 300 mm. The BFR system also includes corner and end sheets for forming wall intersections and closing ends of walls. The overall assembly of the system is illustrated in Figure 1.

PROPOSED BFR MAGAZINE CONFIGURATION

The details of the proposed BFR magazine were provided in Reference 3. The proposed magazine was an earth-covered box structure, 24 feet wide, with a clear ceiling height of 11'-2" and variable length. The proposed headwall was a 300 mm thick BFR wall. The side and rear walls were to be 250 mm thick BFR elements. The roof slab was essentially a conventional reinforced concrete slab, 13 inches thick, using the 300 mm wide BFR face panels on the inner surface as part of the slab reinforcement and as an anti-spalling plate. The structure would be covered with earth, a minimum of two feet thick over the roof, surrounding the side and rear walls, and sloping away from the roof on an incline of 2 horizontal to 1 vertical. The retaining walls, or wingwalls, to support the earth cover at the front of the structure, were also to be 300 mm BFR walls. All foundations were normally reinforced concrete footings. There were two options for the door on the front of the magazine. The first option was to use the sliding, single-leaf steel door, with its accompanying concrete pilasters and header, as detailed in the U. S. Army 33-15-74 standard design. The second option was to use a door constructed of the 200 mm thick BFR section, spanning horizontally, and supported by two BFR pilasters located inside the headwall at the door jambs.

FEASIBILITY STUDY

The first phase of this development effort was a feasibility study [4]. The primary objective of the study was to determine whether the proposed BFR magazine could be used as a standard magazine. As stated above, this magazine must afford the stored explosives sufficient protection to prevent propagation of an explosion, from one magazine to another, at standard intramagazine distances. Therefore, the feasibility study required an independent structural analysis of the BFR concept. As stated above, the ultimate goal of this effort was to develop a structure that would be approved as a standard magazine based only on design. Therefore, we made significantly conservative assumptions about both blast loadings and structural performance.

The BFR magazine structure was analyzed for both static and dynamic loads. The static loads were simply the weight of the structure itself plus the weight of the earth cover. The dynamic loads were those that would be expected from an actual explosion in an adjacent magazine. For the headwall and doors, we used the U. S. Army standard headwall loading derived from the ESKIMO III test [5]. However, for standard magazines, there are no similar loads derived for the buried elements of the structure. In its analysis of the structure, Reference 3 used overpressure loads derived from AC/258, "Manual for NATO Safety Principles for the Storage of Ammunition and Explosives" [6]. These were the predicted overpressure loads on a non-buried, rectangular structure subjected to an explosion of 500,000 pounds of TNT at standard intermagazine distances. These loads were used for our independent analysis. The overpressure loads used for each structural element are given in Table 1.

For the analysis, it was assumed that the BFR walls would perform essentially the same as equivalent, normally reinforced concrete elements. The analysis for static loads was carried out in accordance with ACI 318-89, "Building Code Requirements for Reinforced Concrete" [7]. Analysis for the dynamic loads was performed using the procedures and requirements of the revised U. S. Tri-Service Manual, "Structures to Resist the Effects of Accidental Explosions," TM 5-1300 [8]. Structural details which define the general behavior of the BFR elements were drawn from References 3 and 9. We assumed the face panels to be the principal flexural reinforcement for the elements. Only the portion of the face panels actually on the external faces of the elements were considered. The lacing panels were assumed to behave solely as shear reinforcement. This is a conservative approach because it neglects a portion of the steel that is actually in the wall and does not account for the increased ductility of BFR walls over similar concrete walls.

The dynamic analysis of each element was performed using the computer programs BARCS and SOLVER. BARCS [10] analyzes concrete slabs and beams subjected to blast loads in accordance with the 1969 edition of TM 5-1300 [11]. This program was used to compute moment capacities and resistance-deflection functions for each BFR element. The equations in BARCS that perform these calculations are also valid for the 1990 edition of TM 5-1300. SOLVER [12] is a single-degree-of-freedom (SDOF) dynamic analysis program. It computes velocity, acceleration, and displacement of a SDOF system over time. The results from BARCS and the overpressure loads were used as inputs to SOLVER to determine the maximum dynamic response of each element. The damping ratio used in the analysis was 20% of critical damping.

The maximum deflection limit used as the criteria for incipient failure of the BFR elements was a support rotation of 13.5 degrees. This limitation is drawn from the results of a static test of the 250 mm thick BFR element [3]. In that test, the BFR element experienced the 13.5 degree support rotation without failure of the plastic hinge. Therefore, this failure criteria is conservative.

The preliminary study demonstrated that the BFR system would be an outstanding material to use for standard magazines. The BFR headwall, wingwalls, side and rear walls of the magazine were found to be strong enough to support the static loads and resist the assumed blast loads. The maximum deflections of these elements were less than the support rotation limit. The lacing panels provided sufficient reinforcement to prevent shear failure due to diagonal tension stresses. However, the analysis showed that the BFR walls would not withstand the direct shear stresses at the supports. Diagonal bars would be required as direct shear reinforcement in the final design. The analysis indicated that the proposed roof slab would not comply with the ACI design code, nor would it support even the static loads. A new roof design would be needed. The study established that the BFR door, with additional reinforcement, would withstand the overpressure loads. However, the accompanying BFR pilasters would need to be essentially the same as those used for the sliding steel doors. The weight of the BFR door was more than twice that of the steel door, 10,000 pounds vs. 3,800 pounds, making it harder to operate manually. Also, the BFR door required a track mechanism at the threshold that would be difficult to maintain at some sites and in a long-term storage environment where maintenance might not always be reliable. Therefore, we recommended using the steel doors from existing magazine designs.

VALIDATION OF ANALYSIS METHODS

As part of the feasibility study, the results of several explosive tests of the BFR system were examined. These tests were used to verify the both the general structural analysis methods and, specifically, the assumption that the BFR wall can be predicted to behave essentially the same as an equivalent reinforced concrete slab. We performed an analysis of the BFR structure in each test case using the methods described above. We then compared the computed response to actually performance. This comparison revealed that the predicted deflections were consistently larger than the actual deflections. It also indicates that the BFR walls actually perform better than comparable concrete walls. This confirms that using the methods in TM 5-1300 and assuming the walls to be normally reinforced concrete is conservative.

As mentioned above, our structural analysis used a damping ratio of 20% of critical damping. This is the damping ratio proposed in Reference 3. It is an unusually high degree of damping for normal reinforced concrete elements. A ratio of 3% to 5% is typical, and damping is usually only applied to elastic range of deflections. To determine a usable, reliable damping ratio for design, the explosive test results were again compared to response predicted by the SDOF model. For the analysis, we used the total area of the steel face panels for flexural reinforcement. The results showed that damping ratios of 30% to 50% or even higher were applicable, over the entire range of response, not just the elastic range. To be conservative, 20% damping would be used for the analysis and design calculations.

FINAL MAGAZINE DESIGN

The second phase of the BFR magazine development effort was to produce actual design drawings and details for the magazine. Again, the BFR walls were assumed to perform the same as equivalent reinforced concrete sections. The entire area of the steel face panels was used as flexural reinforcement. Static and dynamic analysis were performed using the same methods as in the feasibility study. The effects of the earth cover were included in the loads and as part of the mass responding to the dynamic loads. However, soil arching and any resulting attenuation of blast effects were neglected, which is quite conservative.

The headwall, side walls, and rear wall were designed to be one-way elements, spanning vertically, with pinned supports. The roof slab was also detailed to be a one-way element, with pinned supports, spanning across the width of the magazine. The one-way spans make it possible to construct magazines in varying lengths with no changes in details. With pinned supports, the walls and roof have less total resistance than if moment-resisting supports were used. This lower resistance in turn reduces the required shear resistance and shear reinforcement requirements.

Design overpressure loads were derived from actual magazine explosive test data. Sources of data included the ESKIMO series of tests [5, 13, 14, 15, 16], the U. S. Air Force Modular Igloo Test [17], and 1/50 scale tests by the Ballistic Research Laboratory [18]. For each structural element, observed overpressure, duration, and impulse data were compiled from the test reports. Where applicable, the data were scaled up to the maximum charge weight of 500,000 pounds of TNT. The data were compared, and the most reasonable and consistent dynamic load was selected for each element. The design loads are listed in Table 2 below.

The intent of the design is to prevent an explosion of 500,000 pounds of TNT in one magazine from creating a sympathetic explosion in adjacent magazines. As a criterion to prevent this propagation, the BFR magazine was designed to remain standing, although suffering severe damage, after such an explosion. For design of the headwall, side and rear walls, and roof, support rotations were limited to 12 degrees, as prescribed in TM 5-1300. This was a design criteria limit. Computed support rotations, given in Table 3 below, were significantly less than 12 degrees. In the event of an accidental explosion, only moderate structural damage is expected to occur. All of the structural elements are expected to remain intact and in place, which should ensure that the explosion does not propagate between magazines.

The steel doors and their supporting pilasters and header were adapted from existing standard magazine designs. Since these doors were designed for the headwall blast load, no analysis of the doors themselves was performed. The pilasters and header are conventional reinforced concrete beams. Since the existing standard reinforced concrete headwall is an two-way element and the BFR headwall is a one-way element, the new pilasters and header were analyzed in detail. All connections were assumed to be pinned, to reduce the ultimate resistance and shear requirements and eliminate the need for moment-resistant foundations. The header and pilasters were designed using the same methods as the walls, as described above. In order to prevent the door from flying into the magazine, support rotations of the pilasters and header were limited to 2 degrees.

The 300 mm BFR wall section was used for the wingwalls. A conventional reinforced concrete foundation was provided. This foundation varies in width with the height of the wall. The wall as designed as a typical cantilever retaining wall. Since the BFR steel panels do not extend into the foundation, additional reinforcement was provided at the base of the wall to provide moment continuity between the wall and the foundation.

FINAL BFR MAGAZINE CONFIGURATION

The final configuration of the BFR magazine is similar to the proposed concept. The interior dimensions of the magazine are the same as originally proposed: 24 feet wide with an 11'-2" minimum clear ceiling height. The length of the magazine can vary from 20 feet to 90 feet; a typical length of 80 feet is shown on the design drawings. The headwall and wingwalls are made of the 300 mm BFR wall cross section. The side and rear walls are the 250 mm BFR cross section. The roof is a concrete slab, 18 inches thick, with a layer of reinforcement in each face. The BFR face panels were omitted from the interior surface of the roof slab, primarily because it will be less expensive to use conventional formwork. The floor of the magazine is a 6-inch concrete slab, sloping toward the front of the magazine. Foundations are normal reinforced concrete strip footings. An elevation view of the BFR magazine is shown in Figure 2. A section through the magazine is shown in Figure 3.

In general, the BFR face panels and lacing panels form the principal flexural and shear reinforcement for the structure. At the base of each wall, "starter bars" extend from the foundation into the wall. These bars are equal in cross-sectional area to the steel face panels. Their length is sufficient to provide static moment capacity, in accordance with ACI 318-89, but not long enough to provide dynamic moment resistance as defined by TM 5-1300. This arrangement provides moment continuity for static loads and during construction, but effectively retains the pinned condition for dynamic loads. Similarly, the roof reinforcement is extended a short distance into the headwall, side walls and rear walls. Again, this provides some moment capacity for static loads but maintains the pinned connection for dynamic loads. Structural details at the headwall are illustrated in Figure 4; details at the side and rear walls are shown in Figure 5.

The BFR magazine design uses the sliding, single-leaf, chain-operated steel doors, as discussed above. The BFR steel panels are discontinued at the edges of the header and pilasters. The design drawings include details for both the 8-foot an 10-foot doors, allowing the final designer to select the door size depending on the needs of the user.

Earth cover a minimum of 2 feet thick is provided over the roof of the magazine and surrounds the side and rear walls. This cover tapers away from the roof on a 2:1 slope and extends a sufficient distance so that the toe of the earth cover will be at the same elevation as the floor of the magazine. The earth over the magazine roof is sloped slightly from front to back to promote drainage away from the headwall.

NON-STRUCTURAL DESIGN FEATURES

Since the magazine is a semi-buried structure, keeping the inside of the magazine dry is a major concern. This problem is addressed by providing positive drainage of water away from the structure and a waterproofing system.

The standard design includes two options for drainage systems. The first option is a sand-gravel filter system. In this system, a contiguous 6-inch thick layer of sand is placed over the roof and adjacent to the side and rear walls, headwall, and wingwalls. A continuous bed of gravel, at the bottom of the sand fill, drains the water to the foundation drain system. The second option is a drainage composite system. This system uses a drainage mat material with a filter fabric backing, which is placed against the roof, side and rear walls, headwall, and wingwalls. It also drains to the foundation drainage system. The foundation drainage system consists of 6-inch diameter perforated pipes sloped to drain toward the front to the structure and out through the magazine headwall and wingwalls.

Waterproofing is provided to prevent water leakage into the magazine and to prevent corrosion of the buried steel BFR face panels. For the sand-gravel filter drainage system, all buried surfaces are covered with a fluid-applied waterproofing membrane. This membrane is covered with a protection board to prevent damage during backfilling. For the drainage composite system, an elastomeric waterproofing membrane is applied to all buried surfaces. Areas of this membrane that are not covered by the drainage composite are also provided with protection board.

Optional ventilation details for the BFR magazine have been adapted from the U. S. Army 33-15-74 standard magazine. Louvers are provided in the headwall. These louvers are spring-operated with a fusible link in order to close in the event of an exterior fire or explosion. The louvers are shielded with heavy steel plates to prevent fragments from entering the magazine. Also, a duct is provided through the rear wall to a ventilator located above the earth cover. Lighting and lightning protection details have also been adapted from the 33-15-74 standard magazine. Interior and exterior lighting is provided with explosion-proof fixtures. Lighting details accommodate the variable length of the magazine. The lightning protection system meets the requirements of DOD 6055.9-STD.

ADVANTAGES OF THE BFR MAGAZINE

There are numerous advantages in using the BFR magazine instead of other standard magazines. Perhaps the most notable advantage is reduced construction cost. The BFR magazine will be less expensive to build than the standard concrete oval arch magazine or the standard steel arch magazine. Cost comparisons, based on an 80-foot long magazine, are shown in Table 4 below. The most significant savings are in the cost of the structure itself and the cost of the earth cover. Much of the cost savings for the structure itself derives from the ease with which the BFR magazine can be built. Erecting BFR walls is no more difficult than building normal concrete walls, and the BFR face panels become in-place forms, reducing formwork costs. Less conventional reinforcing is needed. Also, the rectangular box shape is significantly easier to build than the concrete arch. The steel arch magazine requires the expertise of a specialty contractor for construction. The earth cover for the steel arch must meet specific density requirements to ensure the arch will perform as designed. The BFR magazine has no such requirements. Because of the BFR magazine's rectangular box shape, the overall earth mound is shorter and requires less fill material. The fill volume of the BFR magazine is about 2100 cubic yards, compared to 3500 cubic yards for both the steel and concrete arch magazines.

Another advantage is in the efficiency of use of the storage volume in the BFR magazine. The BFR magazine provides the same storage volume as the concrete oval arch magazine. However, this space is rectangular, allowing easier stacking of boxes or palettes and permitting the use of shorter stacks. This will make handling stored ammunition and explosives easier.

SUMMARY

The BFR magazine has been shown to be sufficiently strong to resist the effects of an explosion on an adjacent magazine at standard intramagazine distances. The design methods used in this effort included a number of conservative assumptions. Actual performance of the magazine, in the event of an explosion, will certainly be better than predicted by the analysis. The magazine will remain essentially intact and will prevent propagation of the explosion to stored explosives.

As of this writing, the design of the BFR magazine is essentially complete. A standard design package has been prepared. This design package includes detailed drawings showing the BFR structure, foundations, earth cover, doors, waterproofing and drainage systems, lighting, lightning protection, and ventilation systems. It also includes technical specifications, a preliminary cost estimate, and a design narrative. The final package will be incorporated in the U. S. Army library of standard designs as the "Magazine, Steel and Concrete Box, Earth-Covered," standard design 421-80-02. This standard design can be adapted for construction at any site. The site adaptation process will generally include verification of the foundation designs for the specific soil conditions, producing site, paving and grading plans, and revising the cost estimate and specifications. Site adaptation does not allow changes in the structure other than defining the desired length of the final magazine. This standard design will be maintained by the Huntsville Division, and will be available by inquiring at the address in Reference 19.

The BFR magazine has not yet been approved by DDESB as a standard magazine. Review of this design by DDESB is in progress. We anticipate that DDESB will approve the BFR magazine as a standard magazine.

Table 1: Blast Loads for Feasibility Study

Structural Element	Overpressure (psi)	Impulse (psi-ms)	Duration (ms)
Headwall & Doors	100	1100	22.0
Side and Rear Walls	44.1	1323	60.0
Roof Slab	44.1	1323	60.0

Table 2: BFR Magazine Design Blast Loads

Structural Element	Overpressure (psi)	Impulse (psi-ms)	Duration (ms)
Headwall & Doors (primary load)	100	1100	22.0
Headwall & Doors (secondary load)	200	1100	10.0
Roof Slab	85	850	20
Side Walls	165	900	10.9
Rear Wall	432	1770	8.2

Table 3: Maximum Support Rotations

Structural Element	Maximum Computed Support Rotations (degrees)
Headwall & Doors	4
Door Pilasters	1
Door Header	2
Roof Slab	2
Side Walls	1
Rear Wall	2

Table 4: Standard Magazine Cost Comparison

	Concrete Oval Arch Magazine 33-15-74	Steel Oval Arch Magazine 33-15-73	BFR Magazine
Excavation and Backfill	$ 78,021	$ 77,275	$ 48,650
Structural Work	153,015	126,541	92,576
Doors	19,568	19,568	19,774
Electrical Work	5,547	5,547	5,554
Waterproofing, Painting, Misc. Metal and Other	23,299	23,749	18,970
TOTAL COST	$ 279,450	$ 252,680	$ 183,048

Note: The total cost of the BFR magazine does not include royalties for patent rights. With royalties of 7.5%, total cost becomes $196,770.

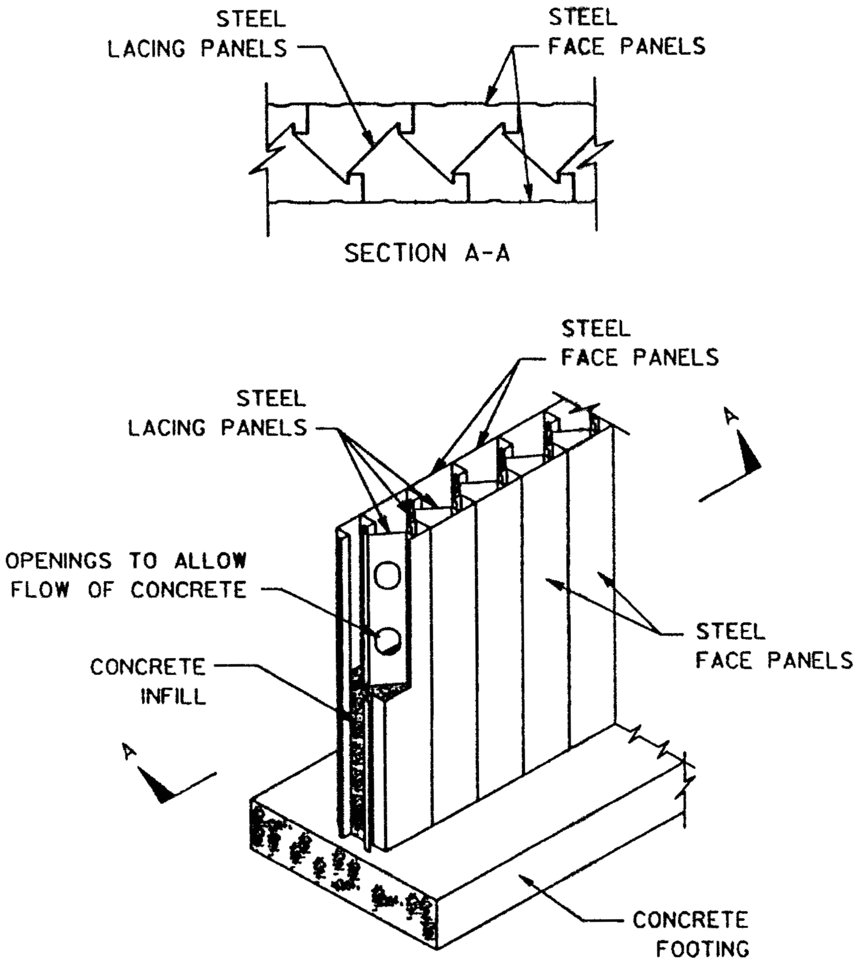
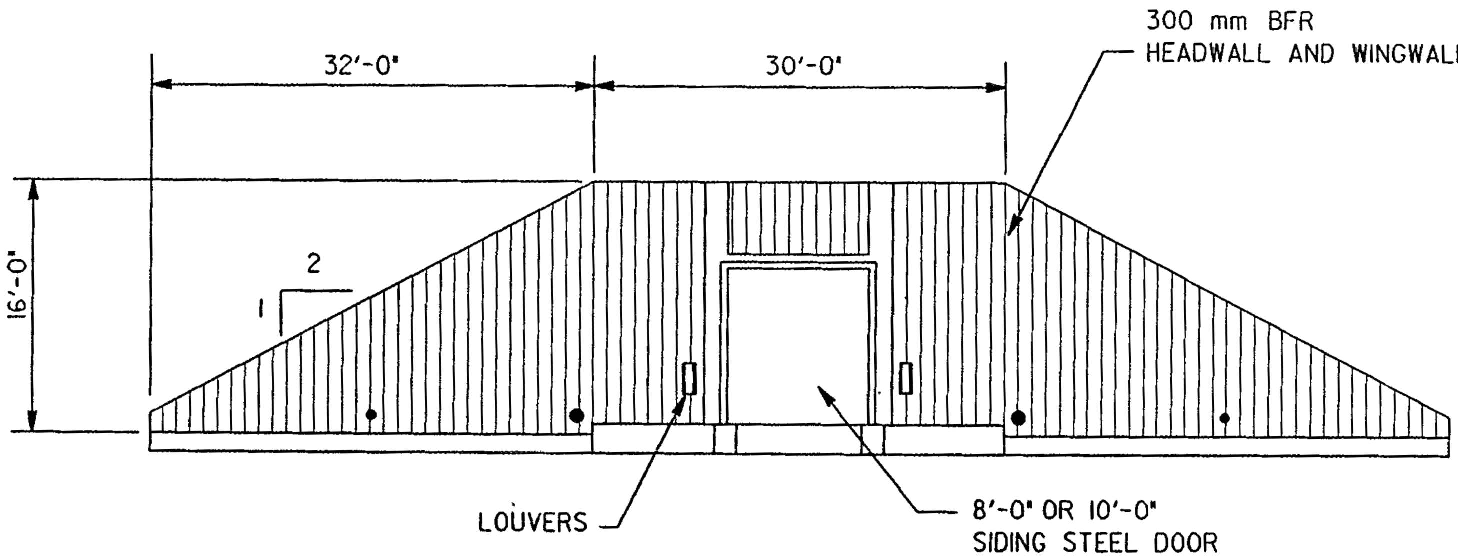


Figure 1: BFR Wall System Details



ELEVATION - BFR MAGAZINE HEADWALL

Figure 2: BFR Magazine Exterior Elevation

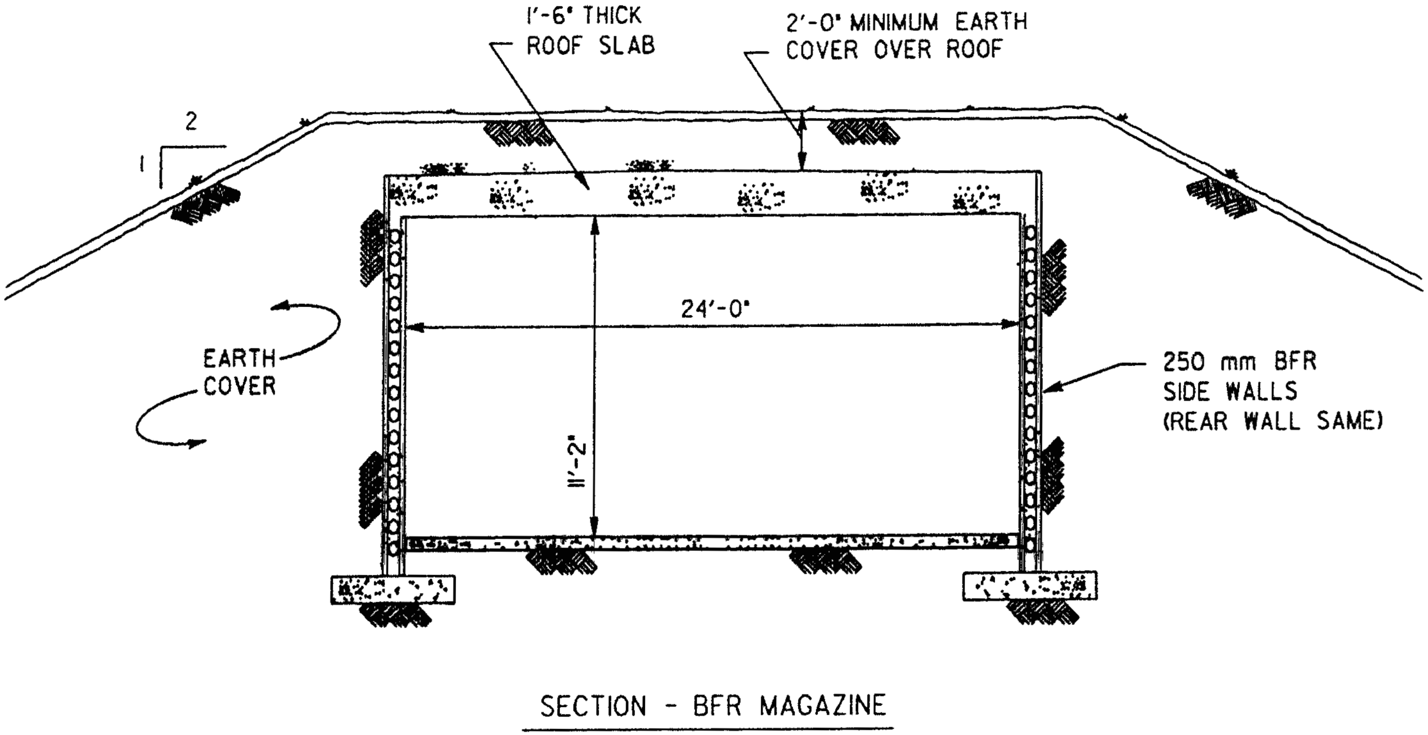


Figure 3: BFR Magazine, Section

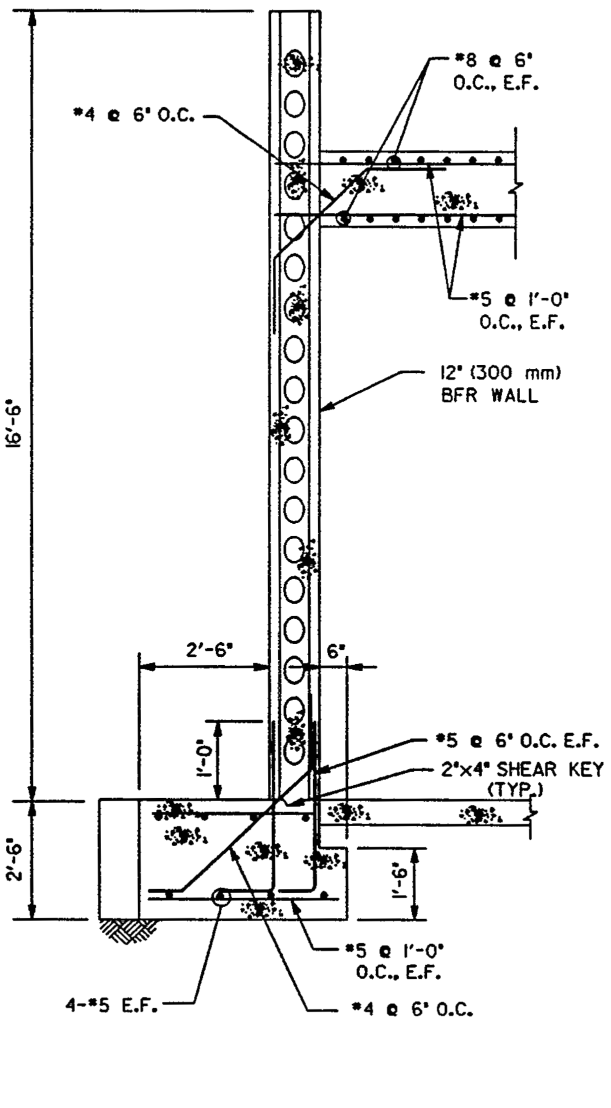


Figure 4: BFR Magazine Headwall Section

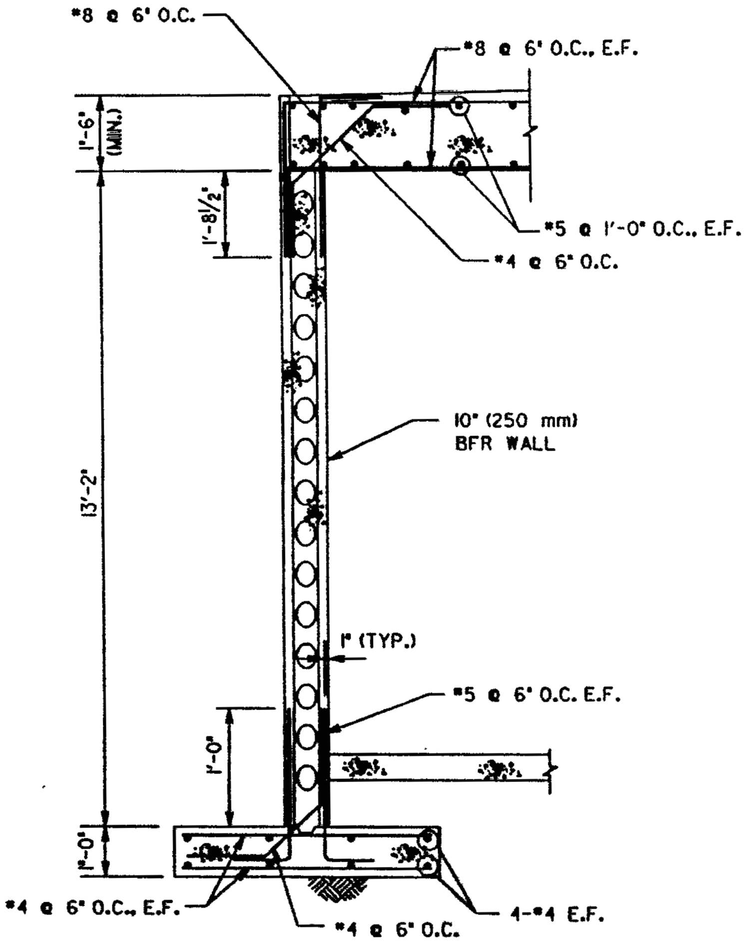


Figure 5: BFR Magazine Side and Rear Wall Section

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19. Commander, U. S. Army Engineer Division Huntsville, ATTN: CEHND-ED-CS, P. O. Box 1600, Huntsville, AL 35807-4301.